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SDIO Phase I SBIR Final Report: "Compact High PRF CO_2 Transmitter".

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I. Summary of Phase I Results.

The Phase I program explored the generation of submicrosecond wide CO_2 laser pulsewidths using a completely sealed-off, non-recirculating pulsed discharge gain medium. Two sealed-off devices with nominal gain volumes of 1.5 mL and 35 mL were utilized in the Phase I program to generate pulses as short as several microseconds at atmospheric pressure and as long as 10 to 20 microseconds at pressures in the 60 to 100 torr region. Sealed-off PRF's from 50 to 500 Hz were used and single-fill lifetimes in excess of 4.4×10^6 pulses were achieved in preliminary experiments.

Using the above sealed-off devices, pulsewidths as short as 500 nsec were shown to be possible using an intracavity gas modulator in conjunction with high level discharge pulsing. The function of the passive Q-switching modulator was to delay the onset of lasing until a higher inversion could accumulate and prevent the re-emergence of a second Q-switched laser pulse when the upper CO_2 laser level re-equilibrates. Q-switching under an enhanced gain-switched envelope produced output pulses with energies up to several mJ/pulse with peak powers in the several KW range. In addition to generating pulsewidths meeting the Phase I goals, the pressure at which the above devices operated was shown to be generally compatible with a single laser that could operate with a cw and energetic short pulse output format.

II. Experimental Results.
(a) Background.

There are two generally accepted and widely used techniques for producing short CO_2 laser pulses. The first is to use a cw pumped discharge and an intracavity optical switch to modulate the Q of the cavity, and the second uses switched discharge to modulate the gain of the medium.

The use of an intracavity EO or AO modulator and a cw CO_2 medium can produce short (ten nsec) or longer (microsec) pulses at PRF's as high as 100 KHz; however, while the medium is sealed-off, output energies from such oscillators are limited to about 100 microjoules per pulse for devices of practical size. If higher output energies are desired, an oscillator-amplifier configuration would be needed.

Conventional high pressure, pulsed discharge oscillators can also generate submicrosecond wide pulsewidths, usually with a large fraction of the output energy appearing in the tail of the pulse, over a very wide range of output energies. At an output level in the range of a few mJ/pulse, no advantage is gained over the above EO or AO modulated MOPA approach because of the requirement for intravacuum gas recirculation at PRF's beyond a few Hz. At higher energies, 100's of mJ/pulse or higher, sealed-off devices are not competitive for the generation of short pulses and larger aperture pulsed discharge oscillators or pulsed discharge MOPA's remain the only practical means to achieve these outputs, even given the many physical and optical disadvantages associated with gas flow. For longer pulses, technological advances in recent years have made sealed-off, non-recirculating pulsed discharge devices competitive to conventional devices to energies in the 1000 mJ/pulse range.

Intracavity EO or AO modulators can be used with conventional high pressure pulsed discharge lasers to further shorten or modify the pulsed output by modelocking, tail clipping, Q-switching or cavity dumping the gain switched output. However, since the modulator will have the limiting aperture in such a transmitter, the range of achievable output energies will be much less than the full potential of a large aperture device. Even for pulsed energies in the range of tens of mJ/pulse, the use of a modulator intracavity to a pulsed discharge laser tends to be unattractive because of the unrelated requirement for gas flow; thus at these approximate energy levels, a modulated oscillator approach with one or more sealed-off amplifiers is usually preferred.

The present Phase I program was directed toward exploring the use of the RF/dc discharge pumping technique at pressures where short CO_2 laser pulses could be generated. This discharge pumping technique employs a short RF pulse to ionize the laser medium between a pair of transversely disposed solid metal electrodes. Connected across the electrodes is a capacitor charged to a potential lower than the self-breakdown voltage for the electrode pair. The generation of an RF discharge between the transverse

electrodes causes the deposition of energy from the capacitor or PFN and, since the deposition of this energy takes place at a voltage lower than the self breakdown voltage of the medium, discharge induced chemistry is minimized. As a consequence of the relatively benign discharge process no gas recirculation is required between successive discharge pulses even to PRF's in the hundreds of Hz range.

The generation of submicrosecond pulsewidths at energies in the few mJ/pulse range in a completely sealed-off, high pressure discharge pulsed CO_2 device represents a significant extension in capability of pulsed discharge laser oscillators. Although only modestly short pulses of several microseconds FWHM were generated in the Phase I program at atmospheric pressure, the fortuitous choice of discharge apertures revealed, along with other cw work, a lower discharge pressure range compatible with **both** cw operation **and** short pulse generation using an intracavity gas modulator to augment very high level discharge pulsing.

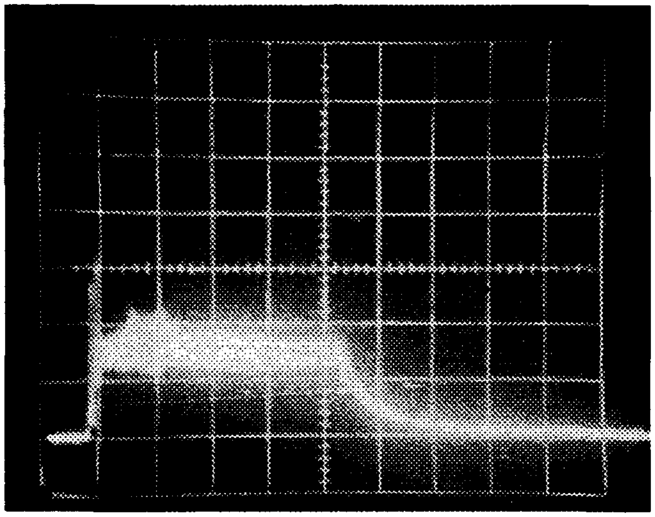
The compatibility of very high level pulsed discharge pumping and concurrent cw discharge pumping in a completely sealed-off CO_2 laser could extend the pulsed output level of an EO or AO modulated oscillator by three orders of magnitude from .1 mJ/pulse to the 100 mJ/pulse level, with pulsewidths as low as 50 nsec at PRF's in the 100's of Hz range. Pulses with energies at the mJ level with pulse-widths as short as 10 nsec using cavity dumping techniques would alsobe possible. With this type of discharge pumping approach, a future dual discharge mode oscillator could be capable of wide range of energetic output pulse formats and a corresponding high level cw output.

II(b). Compatibility of CW and High Level Pulsed Discharge Operation.

It is well known that cw CO_2 lasers using either longitudinal dc or transverse RF excitation, can be discharge pulsed to yield higher output powers. Pulsed laser output from a longitudinal dc excited laser is generated by pulsing the discharge with a pulsed high voltage supply; whereas pulsed laser output from a transversely excited CO_2 device is generated by pumping the discharge with a higher level of RF power. This in turn requires matching both the cw and pulsed discharge impedance levels to the RF source impedance. As a practical matter, pulsing the discharge in a dc excited CO_2 laser is known to significantly reduce device lifetime while no similar effect is observed with RF pumped lasers.

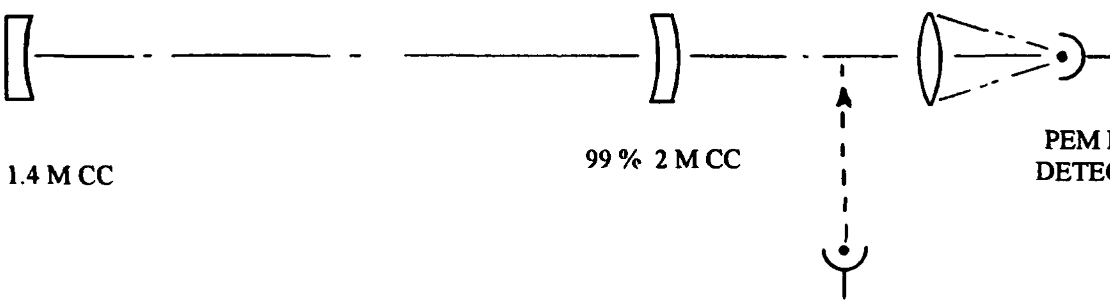
The pulsed laser output shown in **Figure 1**, was generated by pulse modulating the cw RF input power to a transverse RF excited CO_2 laser. For the data shown, a 250 usec wide, 35 watt peak power RF was used to pump a nominal 8.5 cm long gain medium with a discharge aperture of .31 cm^2. If a cw laser is pumped at the nominal cw input level, one would expect that the output pulsewidth should be about as long as the input pulsewidth, and as shown in Figure 1, a

FIGURE 1: GATED CW OUTPUT



3.3 W

50 uSEC / DIV



TEST CONDITIONS:
60 TORR, 1 - 1 - 6 + 5 % Xe, 350 mW @ 500 Hertz, 1.6 Watts CW, GAIN LENGTH = 8.5 cm

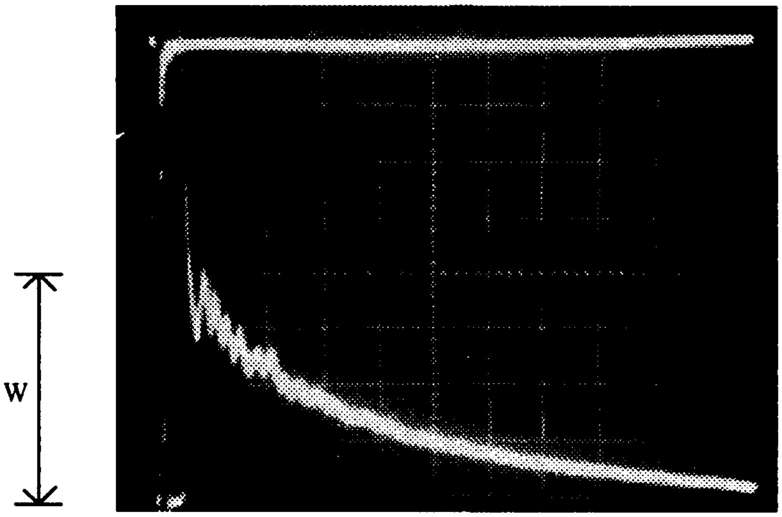
220 usec wide output pulse results. At a discharge PRF of 500 Hz, the average output power of this laser was measured to be 350 mW, corresponding to an output of .7 mJ/pulse. By integrating the area under the displayed pulse envelope and equating it to .7 mJ one can determine that the laser output was 3.3 watts; this output also corresponds to 350 mW divided by the .1125 output duty cycle.

With a 100% cw input of 35 watts, the same laser, operating under identical conditions of pressure (CO_2-N_2-He:1-1-8 + 5% Xe at 60 Torr) emitted an output of 1.6 watts. Thus by pumping the discharge at the nominal cw input level with an input duty cycle of only 12.5% (500 Hz, 250 usec), the peak envelope output power of the laser can be increased from 1.6 watts to about 3.3 watts. The 3 dB increase in "peak" laser output power is a result of the higher gain and the lower temperature of the active medium. The above cw and pulsed output data was taken with a pair of transverse planar stainless steel electrodes, however, a similar increase in peak output power is observed with a variety of gas mixtures with pressures in the 50 to 100 torr range using an upper planar stainless steel electrode and a lower stainless steel electrode with a Chang profile.

Since the RF discharge pulse was used to trigger the displayed trace in Figure 1, the room temperature PEM HgCdTe (MCT) detector output shows that about 50 usec is required for the laser to reach oscillation threshold when pumped at the cw input level. One would expect this 50 usec buildup period to decrease if the discharge were to be pumped with a higher input power, and as shown in **Figure 2(a)**, the delay between discharge pumping and the onset of laser output can be decreased significantly with high level discharge pumping. In order to generate the data in **Figure 2(a)**, the cw laser used above was modified by replacing the lower 8.5 cm long grounded planar electrode with a 6.25 cm long grounded Chang electrode and operated with a CO_2-N_2-He:1-3-18 gas mix at a pressure of 100 Torr. As shown in **Figure 2(b)**, the 50 usec delay to reach oscillation threshold with nominal cw pumping can be reduced to 5 usec when the discharge is pumped significantly above the cw level. In this case the discharge is excited by first applying a 7 mJ, 1 usec wide RF ionization pulse to the planar-Chang electrode pair; this in turn commutes an additional 67 mJ of dc energy into the discharge from a 67 nF capacitor (1500 V to 500 V). **Figure 3** summarizes some of the characteristics of this pulsed discharge laser.

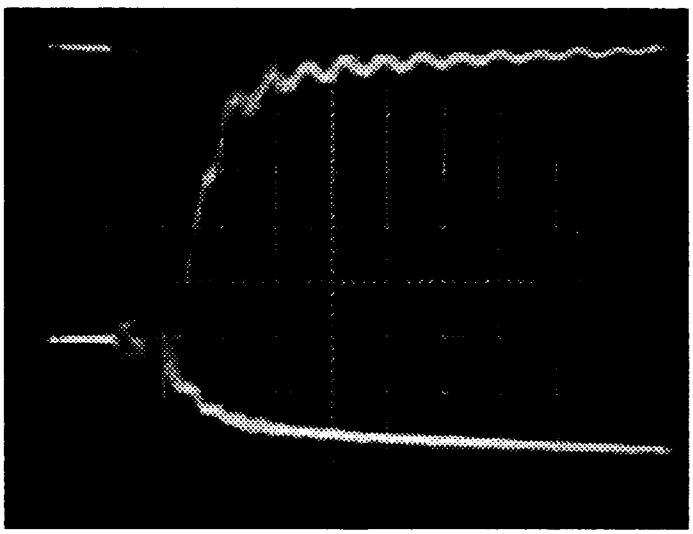
Based on the 6.25 cm long region of discoloration on the above transverse electrodes, the discharge volume was estimated to be in the range of 1.5 to 1.8 mL and with a total per pulse input energy of about 74 mJ (67 mJ of dc and 7 mJ of RF) the 100 Hz PRF, sealed-off medium is found to be pumped at over 300 J/LA. Approximately half of the 67 mJ energy stored in the 67 nF capacitor is seen to be commuted into the discharge volume in 250 ns, thus significant discharge pumping is occurring at a level of 34 mJ/250 ns = 136 KW or nearly 3900 times the cw level.

FIGURE 2: HIGH LEVEL DISCHARGE PULSED OUTPUT



123 W

10 uSEC / DIV



20 A / DIV

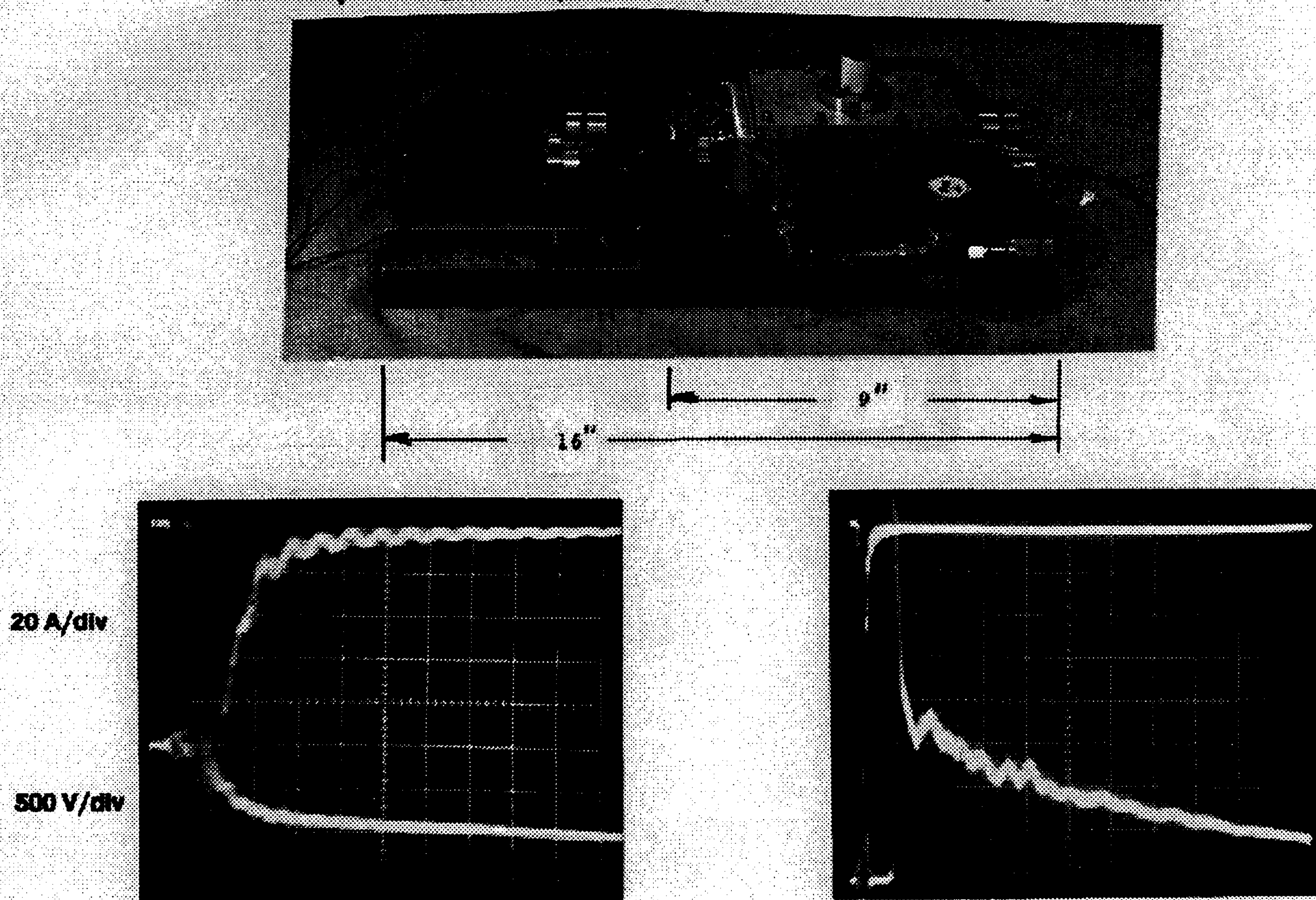
500 V / DIV

500 nSEC / DIV

TEST CONDITIONS: 100 TORR, 1 - 3 - 18, 200 mW @ 50 Hertz, GAIN LENGTH = 6.25 cm, 67 nF STORAGE CAPACITOR, SPECIFIC INPUT 300 J / LA

FIGURE 3:
SEALED - OFF, HIGH PRF, PULSED RF / DC CO_2 TE LASER

Best non-simultaneous performance: 250 Hz, 4 mJ/pulse output, 3.7% efficiency, 4.4×10^5 pulses @ 100 Hz, sealed-off, 200A 400 ns FWHM pump duration



Current, voltage waveforms: 500 ns/div

Laser output: 5 usec/div

Using the PRF of the laser and the average output power, the laser output energy was determined to be 4 mJ/pulse, and by integration of the area under the laser pulse, the peak laser output power was calculated to be 123 watts as shown in Figure 2(a). Although the photographed data in **Figures 1-3** were not taken under identical conditions, because cw operation very much like that shown in Figure 1 (about 1 watt cw output was extracted from the 6.5 cm long active medium at a pressure of 100 torr using the Chang electrode), it is clear the above experiments illustrate it is possible to operate a nominal 5.5 mm bore device in the pressure range of 60 to 100 Torr with either a cw or a very high level pulsed discharge.

When the data taken using different electrode lengths (6.25 cm vs. 8.5 cm), shapes (Chang vs. planar), pressures (100 torr vs. 60 torr) and nominal cw output powers (1 watt vs. 1.6 watts) are compared, the pulsed RF/dc output is seen to be approximately 100 times higher than the cw output (123 watts vs. 1 watt).

II(c). Pulsed only High Pressure Operation.

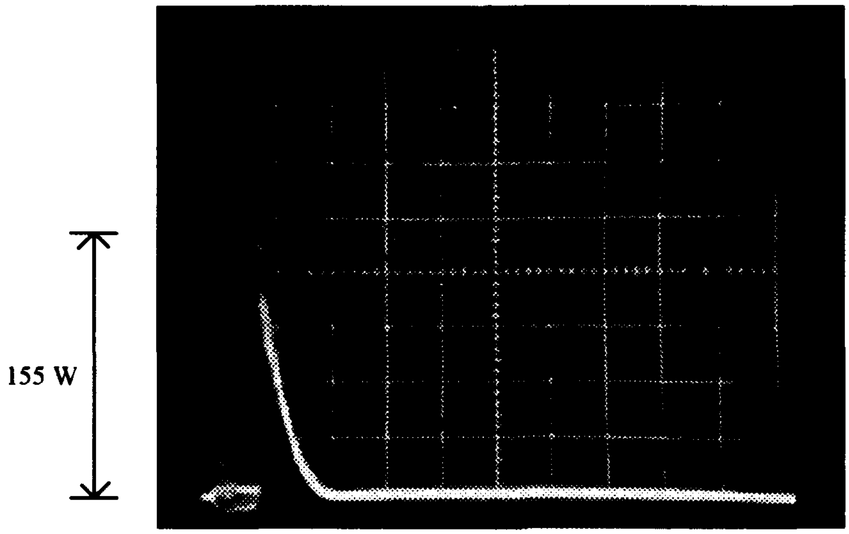
CW laser operation beyond 150 torr was not specifically pursued with the above 6.25 cm gain length, 5.5 mm bore device, because, as one might expect, uniform cw discharges were increasingly more difficult to establish at higher pressures. Although cw laser operation at the higher pressures could have been improved by decreasing the transverse electrode spacing, this would also have the undesired effect of decreasing the volume of active medium for any subsequent pulsed laser experiments.

As shown in **Figures 4 and 5**, shorter output pulses could be generated with discharge pulsing at higher pressures. This data, like the previous lower pressure cw and lower pressure pulsed data, was taken with freespace Gaussian cavity lengths that varied between 10 to 25 cm, with most of the data being taken with specific discharge input energies approaching the region where discharge stressing was observable. In all cases, the laser output was measured separately with an average power meter and by focusing the output of the laser onto a PEM type room temperature HgCdTe detector; the peak laser output then being determined by integrating the displayed pulse shape.

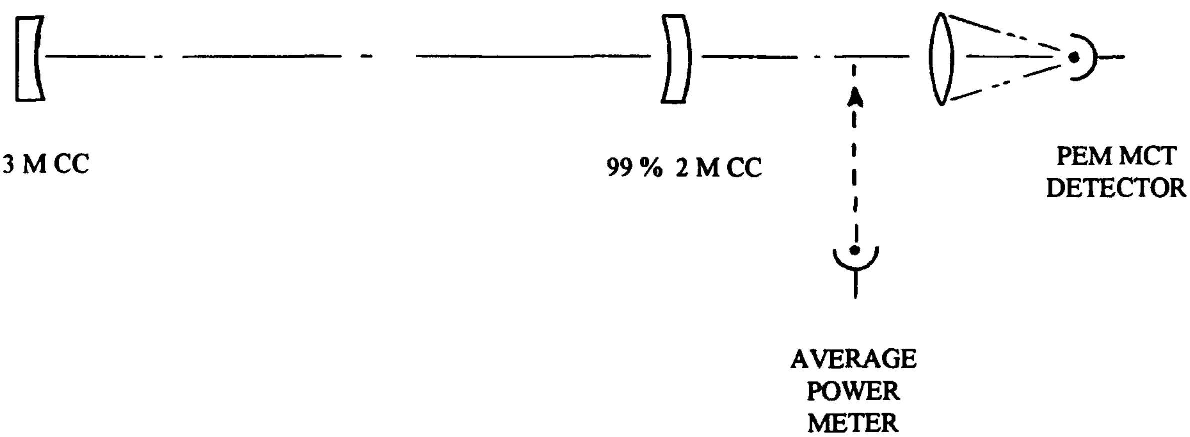
Pulsed output energies for the three cases shown in Figures 4 and 5 were in the range of .3 mJ/pulse to .75 mJ/pulse, and because of the faster kinetic processes at these higher pressures the output pulsewidths were shorter than those generated at pressures in the 60 to 100 Torr range. As a result of the shorter pulses, the peak output powers were somewhat higher in the 560 to 760 Torr range, to as high as 225 Watts with the CO_2-N_2-He:1-3-18 mix at 750 Torr. Also, as with the lower pressure data the delay time to reach laser threshold was about 5 usec.

Discharge pumping at high pressures can therefore result in the

FIGURE 4: HIGH PRESSURE PULSED OUTPUT



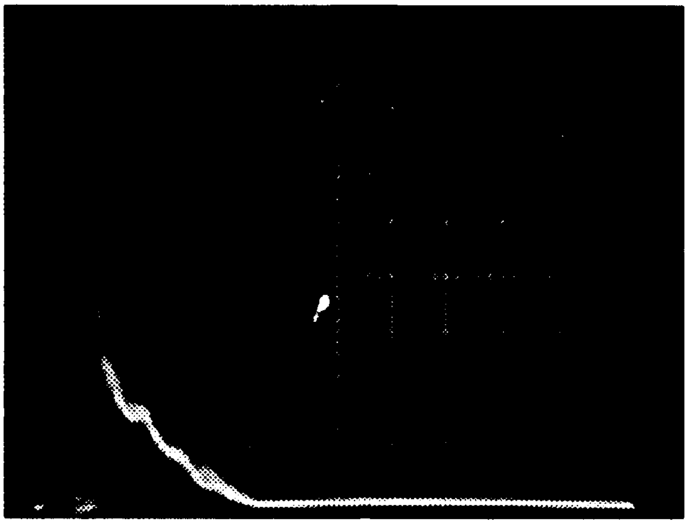
5 uSEC / DIV



TEST CONDITIONS: 560 TORR, 1 - 1 - 6 + 5% Xe, 15 mW @ 50 Hertz, GAIN LENGTH = 6.25 cm
INPUT ENERGY = 30 mJ or 25 J / LA

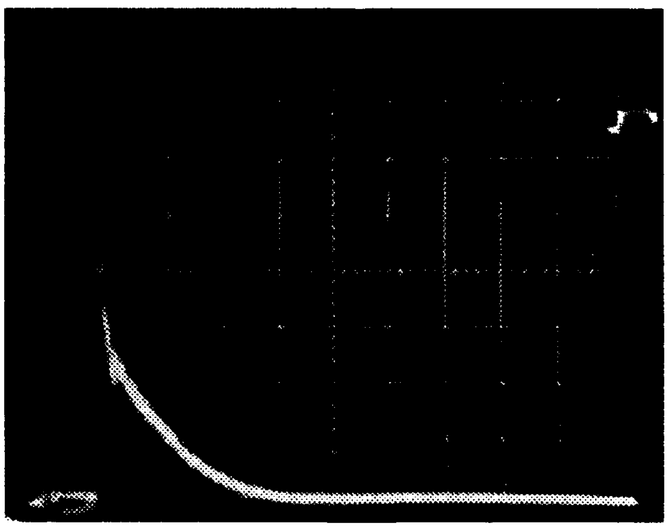
FIGURE 5: HIGH PRESSURE PULSED OUTPUT

225 W



5 uSEC / DIV

112 W



5 uSEC / DIV

TEST CONDITIONS

UPPER: 750 TORR, 1 - 3 - 18, 150 mW @ 200 Hertz, INPUT ENERGY 70 mJ or 39 J / LA

LOWER: 560 TORR, 1 - 3 - 18, 20 mW @ 50 Hertz, INPUT ENERGY 40 mJ or 30 J / LA

generation of peak laser output powers about 100 times the level observable from a low pressure cw laser of the same length. However, while the pulsewidths were shorter at high pressure, no cw laser operation was possible because cw discharges could not be maintained with the chosen electrode spacing at these pressures.

Thus at both low and high pressure: (1) mJ/pulse outputs are possible with high level discharge pulsing, (2) peak powers up to 100 times the output level of a comparable length cw laser are possible, and (3) high (few 10^2 Hz minimum) PRF's can be realized using a completely sealed-off device. However, while somewhat shorter pulses can be generated at high pressure, both energetic cw and pulsed discharge operation were only possible at the lower pressures (60 to 100 Torr) for the nominal 5.5 mm bore device used.

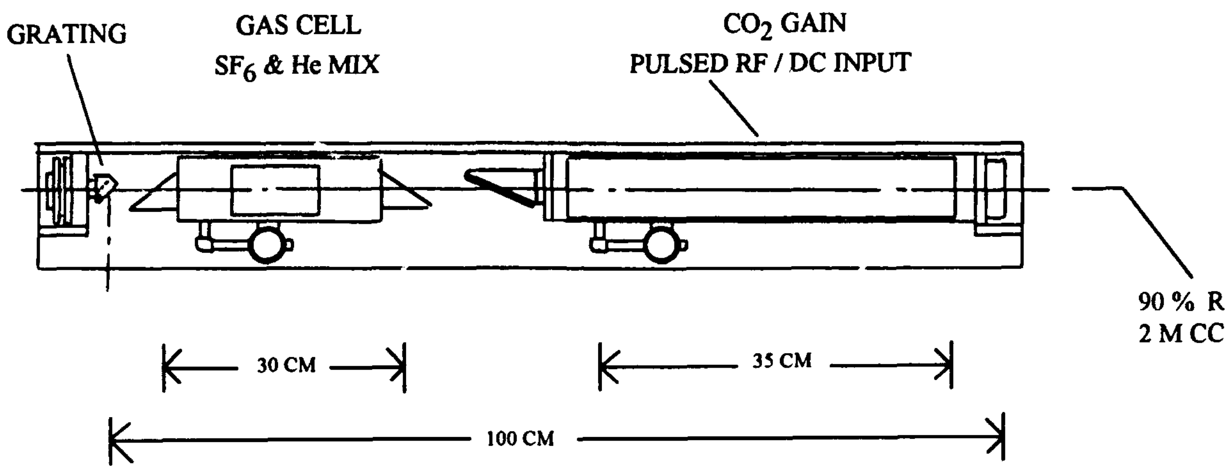
II(d). Pulsed Discharge Operation with Cavity Modulation.

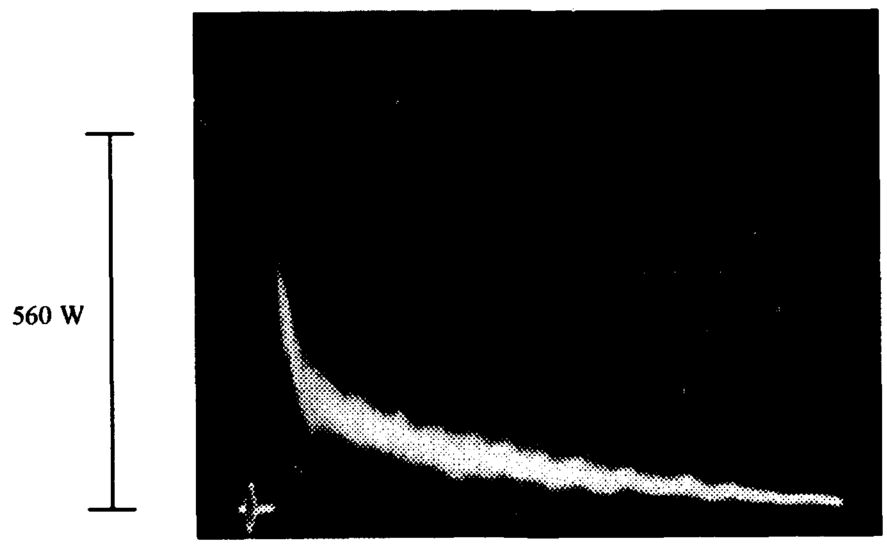
The specific output energies generated with the small nominal 1.5 mL laser above are attractive for some DOD applications, such as rangefinding, wind sensing and clear air turbulence detection, specifically with respect to the sealed-off nature of the device. Unfortunately, the pulses are too long for most DOD type missions. If shorter pulses could be achieved at these energy levels using an intracavity modulator to augment the high level discharge pulsing, then such an oscillator arrangement could compete directly with an actively modulated cw discharge MOPA approach.

One robust type of gas modulator can be readily made using a simple vacuum cell with a pair of Brewster windows, and as shown in **Figure 6(a)**, placed intracavity to a sealed-off pulsed RF/dc laser having a resonator length of 100 cm, a g value of 1/2 and an output mirror reflectivity of 90%. The 9.5 mm diameter ceramic tube, with a 30 cm window to window length was sealed at either end with a pair of ZnSe Brewster windows and was filled to a pressure of about one or two Torr with a mixture of He and SF_6 in the approximate ratio of 500:1. This cell functions as a passive Q-switch, which can delay the onset of laser oscillation by 5 to 10 usec after the high level discharge excitation cycle is completed.

The active medium for the gain-switched, Q-switched experiments used a 1 cm^2 by 35 cm long RF/dc pumped device operating with various gas mixtures in the 60 to 100 Torr range. The output pulse shape of **Figure 6(b)**, which was taken at a medium pressure of 100 Torr with a CO_2-N_2-He:1-3-18 gas mix, when the medium was pumped by commuting 475 mJ/pulse from a 250 nF capacitor charged to 2000 Volts. At this pumping level, the specific discharge input energy of both RF and dc was 120 J/LA. For the data shown in **Figure 6(b)**, with an evacuated cell, the output power was 320 mW at a PRF of 50 Hz, or 6.4 mJ/pulse with the above pumping levels. The corresponding peak laser output power of 480 Watts was determined by integrating the output pulse shape of **Figure 6(b)** as measured with a TEM type room temperature HgCdTe detector terminated in 50 ohms.

FIGURE 6: GAIN SWITCHED, Q - SWITCHED CAVITY





10 uSEC / DIV

TEST CONDITIONS: 100 TORR, 1 - 3 - 18, 320 mW @ 50 Hertz, INPUT ENERGY = 550 mJ or 120 J / LA

A typical output energy for the laser with the grating but without the cell was in the range of 20 mJ/pulse.

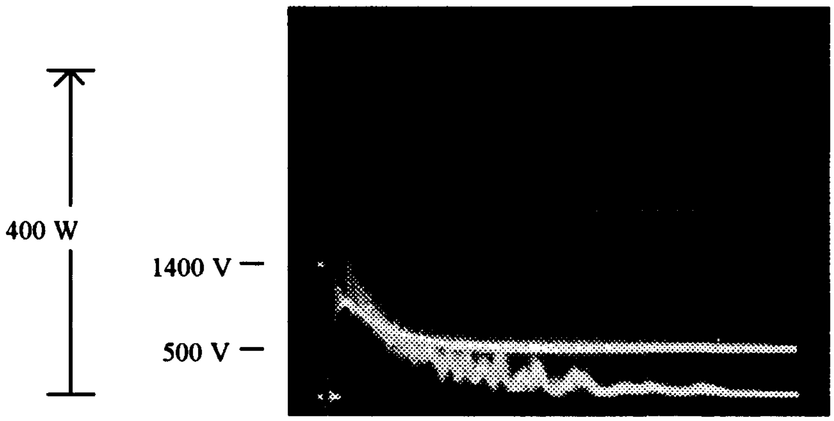
The sequence of three photographs in **Figure 7** illustrate the effect of Q-switching and gain-switching first with an empty cell and subsequently using a weak mixture of SF_6 and He in the passive modulator cell. **Figure 7(a)** shows both the commuted voltage on the discharge storage capacitor (500 V/div) and the MCT laser output pulse (62 W/div) when the cell was empty and the laser medium was a 60 torr, 1-1-8:CO_2-N_2-He laser mixture with 5% Xe. Approximately half of the energy stored in the 250 nF capacitor was commuted into the RF ionized discharge well before laser threshold was reached, about 4 usec after discharge pumping was initiated. Some discharge pumping can be observed after this time as the 250 nF capacitor continued to be discharged from a maximum of 1400 V to the minimum of 500 V. The peak laser output power of 404 watts was determined by integrating the MCT detector output and equating the area to 2.8 mJ/pulse (140 mW at a PRF of 50 Hz).

The effect of the passive Q-switching cell is seen to delay lasing from the normally observed 4 usec as shown in **Figure 7(a)** to about 12 usec as shown in **Figure 7(b)**. Under these conditions, the empty cell output of 2.8 mJ/pulse was reduced to .7 mJ/pulse when the cell was filled with a 500:1 He:SF_6 mixture to a pressure of 2 Torr. This energy reduction is roughly consistent with upper level rotational state re-equilibration. At the same time, the peak laser output was increased to nearly 2200 Watts as determined by integrating the display in **Figure 7(c)**. This enhancement in output power is due to the higher gain developed and the larger inversion accumulated by delaying lasing an additional 8 usec **(Ref 1,2,3,4.)**.

Figure 8(a) and **8(b)** illustrate the relative enhancement in output power and delay required to reach laser threshold when the gain medium of Figure 7 was pumped with about 750 mJ/pulse at a PRF of 50 Hz. Under these conditions of pumping, the 4 mJ/pulse output energy decreased to 1 mJ/pulse when the cell was filled with a passive Q-switching SF_6-He gas mix, however, at the same time the peak laser output power increased to over 2100 W with a FWHM pulsewidth of 750 ns.

Figure 9(a) shows the output pulse shape when a 1-1-3:CO_2-N_2-He lasing mix was discharge pulsed at a pressure of 100 torr. In this case the empty cell output energy was 5 mJ/pulse with a FWHM pulsewidth of 8 usec, while the Q-switched, gain-switched output was 1.5 mJ/pulse with a FWHM pulsewidth of 500 to 600 nsec. The peak laser output power of 5200 Watts under these conditions is competitive with Q-switching and cavity dumping of a cw discharge device, while the level of output energy is competitive with actively modulated MOPA systems. With much higher cell pressures (10-20 Torr) and much more dilute SF_6 passive Q-switching gas mixtures, essentially all the empty cell energy could be made to appear in a series of narrow pulses with a pulse separation of a few usec, as shown in **Figure 9(b)**.

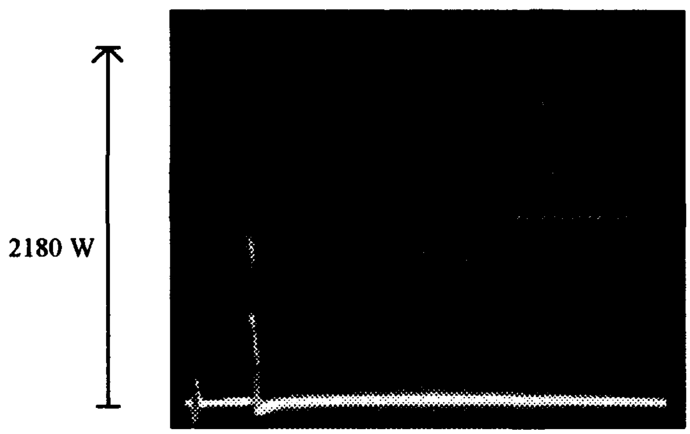
FIGURE 7: GAIN SWITCHED, Q - SWITCHED OUTPUT



10 uSEC / DIV

2.8 mJ / PULSE @ 50 Hertz

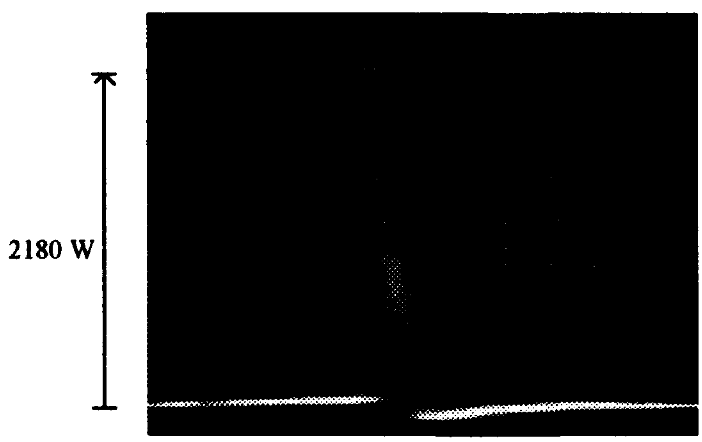
CELL EMPTY



10 uSEC / DIV

0.7 mJ / PULSE @ 50 Hertz

CELL PRESSURE = 1 TORR



1 uSEC / DIV

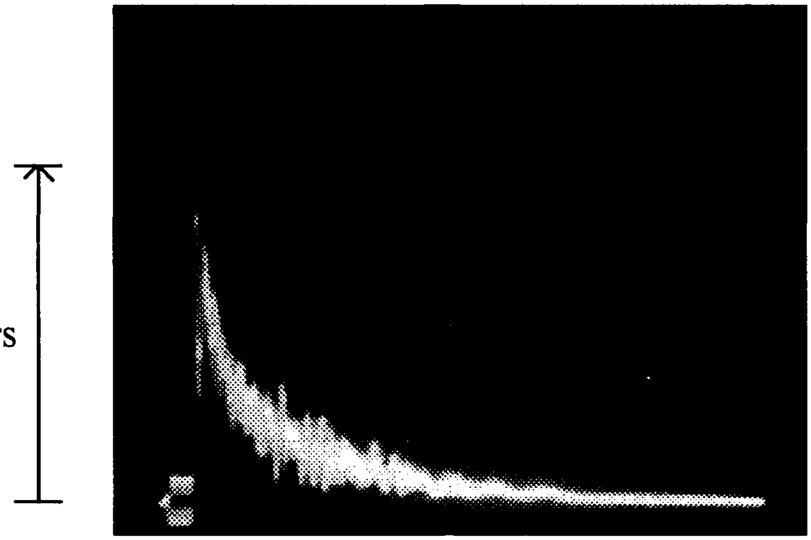
0.7 mJ / PULSE @ 50 Hertz

CELL PRESSURE = 1 TORR

TEST CONDITIONS: 60 TORR, 1 - 1 - 6 + 5% Xe

FIGURE 8: GAIN SWITCHED, Q - SWITCHED OUTPUT

420 WATTS

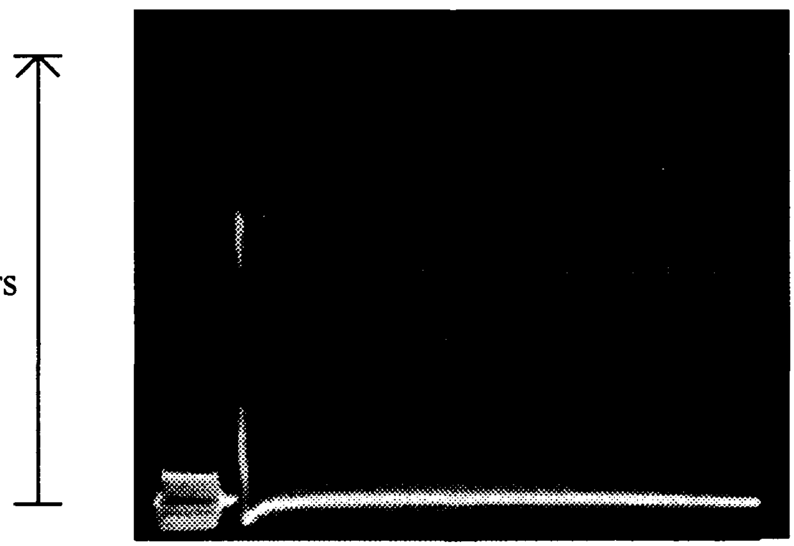


4 mJ / PULSE

CELL EMPTY

10 uSEC / DIV

2140 WATTS



1 mJ / PULSE

CELL PRESSURE = 1 TORR

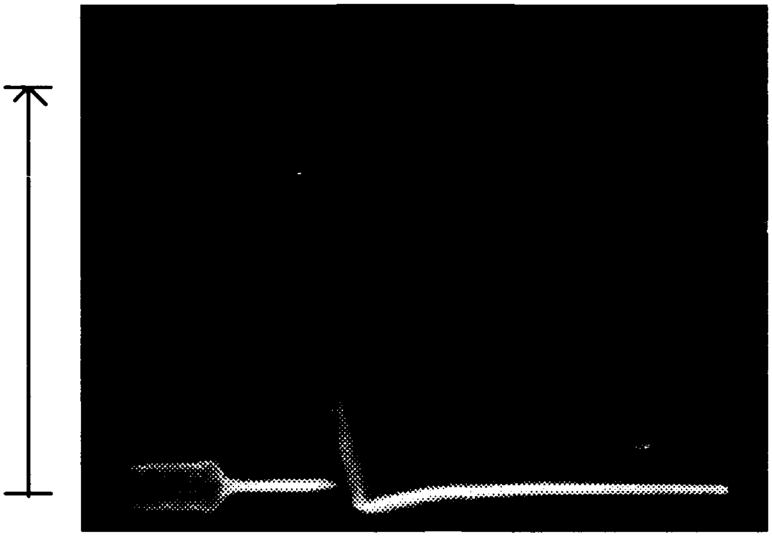
500 : 1 He : SF_6

10 uSEC / DIV

TEST CONDITIONS: 60 TORR, 1 - 1 - 6 + 5% Xe, 10P20, 50 Hertz

FIGURE 9: GAIN SWITCHED, Q - SWITCHED OUTPUT

5200 W



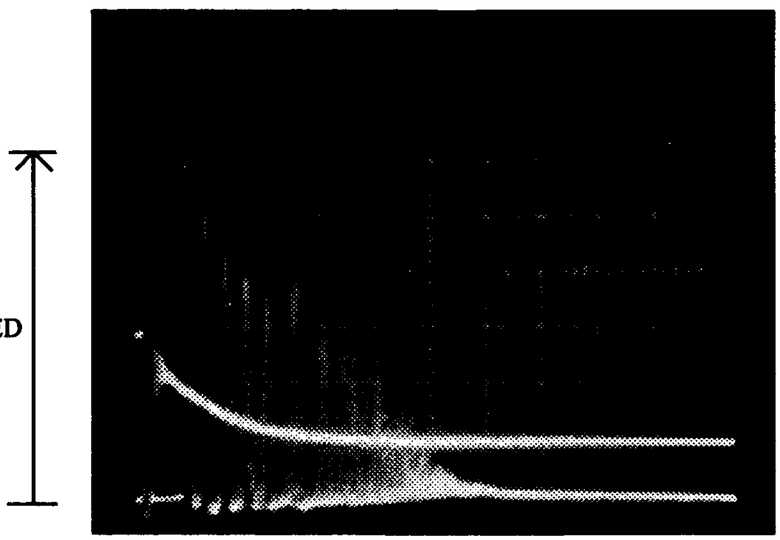
1.5 mJ / PULSE

CELL PRESSURE = 1 TORR

He + SF_6

2 uSEC / DIV

UNCALIBRATED



4 mJ / PULSE

CELL PRESSURE = 20 TORR

He + SF_6

10 uSEC / DIV

TEST CONDITIONS:
UPPER: 100 TORR, 1 - 1 - 3 + 5% Xe
LOWER: 100 TORR, 1 - 3 - 18
BOTH 50 Hertz PRF

The data of **Figures 6 to 9** clearly illustrate that gain-switching, generated with very high level discharge pumping can be combined with cavity Q-switching controlled by an intracavity gas modulator to generate mJ or greater laser pulses with FWHM durations of less than 750 ns. Higher output energies could be achieved by increasing the pulsed discharge laser efficiency and using a modulator with an aperture compatible with the laser medium aperture.

III. Conclusions.

A completely sealed-off, small discharge volume, nominal 5.5 mm bore CO_2 laser was shown to produce mJ level output pulses with FWHM durations in the 10 to 20 usec range by using high level discharge pumping at pressures of 60 to 100 Torr. Likewise, gated cw and 100% cw operation of this device was also demonstrated in this pressure range.

A larger discharge volume device also using high level discharge pulsing was likewise shown to be capable of generating 10 to 20 usec wide laser pulses with pressures in the 60 to 100 Torr range and further these pulses could be shortened to under 1 usec FWHM by employing an intracavity gas modulator. The observed pulse shortening was accompanied by a substantial increase in peak laser output power, consistent with the accumulation of an enhanced inversion; while the observed mJ level output energies with the active cavity modulation were compatible with upper level dynamics at the operating pressure.

Taken together, the two sets of experiments performed with the smaller and larger gain volumes suggest that it would be possible to generate both an energetic cw laser output and an energetic multi-format short pulse laser output from the same device. This would be accomplished by using RF/dc excitation and operating at pressures where cw and high level discharge pulsing are compatible and also by using an intracavity Q-switching modulator to augment gain-switched high level discharge pulsing.

IV. References

(1) Piltingsrud, Appl Opt, Vol 30, No 27, 20 Sept 1991, pp 3952-3963.

(2) Bae et al, IEEE JQE, Vol 25, No 7, July 1989, pp 1591-1594.

(3) Bluyssen et al, IEEE JQE, VCol 16, No 12, Dec 1980, pp 1347-1351.

(4) Private Communication, Dr. Harvey V. Piltingsrud, NIOSH, Cincinnati, OH.